Inclinometer casings retrofitted with acoustic real-time monitoring systems

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Abstract

The paper details the concept of retrofitting inclinometer casings with active waveguides in order to provide subsurface instrumentation that can monitor the stability of slopes continuously and in real-time. The operation of the active waveguide, the unitary battery operated Slope ALARMS acoustic emission sensor and warning communication system are described. A field trial previously reported by the authors demonstrates that acoustic emission rates generated by active waveguides are proportional to the velocity of slope displacements, and can therefore be used to detect changes in rates of movement (i.e. accelerations and decelerations) in response to destabilising (e.g. rainfall) and stabilising (e.g. remediation) effects. The paper presents the results of a field trial of the acoustic monitoring system retrofitted inside an inclinometer casing in a reactivated landslide at Hollin Hill, North Yorkshire, UK. The study demonstrates that this approach can provide continuous information on slope movements with high temporal resolution. Converting manually and periodically read inclinometer casings into continuously monitored active waveguides using Slope ALARMS sensors is a cost effective solution to provide real-time information that could be used in the protection of people and infrastructure.

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1. Introduction

Landslides cause many thousands of fatalities each year around the globe. Petley (2012) reported records of over 32,000 fatalities that resulted from landslides during the period 2004 to 2010. A large majority of these fatalities occurred in Asia, along the Himalayan Arc and in China. Fatalities from landslides in the UK are rare, but the cost to maintain and remediate infrastructure and the built environment as a result of slope instability is high. The UK is home to tens of thousands of kilometres of transport links and utilities, and many thousands of flood embankments and water retaining earth structures. The operation of this infrastructure is critically dependent on the performance of the cutting and embankment slopes of which they are constructed. The transient elevations in pore-water pressures that occur in response to periods of prolonged and/or intense rainfall are the main trigger of slope instability in the UK. The UK has recently experienced a significant increase in the occurrence of slope instability incidents (e.g. in response to the wet summer and winter of 2012, and winter of 2013). This has had a major impact on geotechnical assets; particularly transport networks (i.e. road and rail). There is evidence that such engineered slopes are deteriorating over time. Seasonal cycles of wetting and drying induce cycles of pore-water pressures, effective stress and straining (i.e. seasonal ratcheting (Take & Bolton 2011)). This can lead to localised strain softening and eventually progressive failure. The significance of this is that slopes are failing in response to rainfall events that they could have survived in the past. Although reactivated landslides (i.e. slopes with a pre-existing shear surface at or close to residual strength that therefore experience little or no further brittle loss of strength) result in small low velocity movements in response to seasonal pore-water pressure oscillations (Hutchinson 1988; Leroueil 2001), they still cause annual expenses over consecutive years in the order of millions of pounds due to structural damage, insurance costs, engineering measures and remediation (these cost estimates relate mostly to direct effects and little information is available on indirect costs associated with disruption to traffic and the local economy) (Gibson et al. 2013). Changing climate patterns forecast for the UK are expected to result in more intensive rainfall in winter months and therefore a more regular occurrence of extreme rainfall events (Dijkstra & Dixon 2010). Slope instability therefore poses a significant threat and is expected to become more severe in the future. Railway derailments and catastrophic collapse of water retaining earthworks are among the major hazards. The cost of emergency repair in response to slope failures can be ten times greater than the cost of planned maintenance if conducted prior to collapse. This highlights the growing need for effective real-time monitoring; to detect and communicate slope instability to allow for responsive action to be taken (e.g. evacuation or remediation).

There is a clear need for affordable instrumentation that can provide continuous, remote, real-time information with high temporal resolution on slope movements for use in the protection of people and infrastructure by practitioners and operators. Current systems are either too expensive for wide-scale use or have technical limitations. Subsurface measurements are known to provide reliable information and inclinometer casings are routinely installed in slopes where it is anticipated shear surfaces exist or could form. A significant cost element for these installations is associated with forming the borehole for installation of the casing, particularly in rail applications where site access is restricted and costly (i.e. to meet health and safety requirements). In the large majority of applications these casings are read periodically during scheduled site visits (i.e. typically a few times a year) and hence only provide information on historical slope movements (i.e. that have occurred since the last reading). This mode of operation cannot provide continuous measurements or real-time information for use in an early warning system. An option is to install in-place inclinometers for continuous measurement of ground deformations, and these can be linked to communication systems to provide warnings when threshold values are exceeded. ShapeAccelArray (SAA) systems are also available to provide this type of information. However, these in-place continuous deformation measurement systems are relatively high cost to purchase and operate, and this means that their use is currently limited (i.e. only a small percentage of subsurface deformation measurement systems provide continuous measurements and real-time information that can inform decisions by operators of infrastructure).

An approach, Assessment of Landslides using Acoustic Real-time Monitoring Systems (ALARMS) based on detecting and quantifying acoustic emission (AE) generated by an active waveguide installed through a deforming soil slope (Dixon & Spriggs 2011) has been developed and trialled using unitary battery operated sensors. This paper summarises the AE measurement system and the communication system that is used to disseminate warnings of movement based on trigger levels related to slope displacement rates, and the concept of retrofitting inclinometer casings with such systems is introduced to provide capability for continuous measurements and real-time information. Measurements from a field trial of a retrofitted inclinometer casing in a reactivated landslide at Hollin Hill, North Yorkshire, UK are presented. The results demonstrate the ability of the monitoring system to provide continuous information on slope movements with high temporal resolution. The Slope ALARMS system is shown to be capable of detecting slope movements and providing information that can be communicated to responsible persons/systems to allow for relevant action to be taken (e.g. send an engineer to inspect the slope or manage traffic).

2. Acoustic emission monitoring of slopes

2.1. The active waveguide

Deforming soils generate AE stress waves which propagate through materials surrounding the generation source. Granular soils (e.g. sand and gravel) produce relatively high magnitude AE signals that can propagate several metres along a waveguide (e.g. steel rod or tube) without suffering significant attenuation (Koerner et al. 1981; Dixon et al. 2003). Fine grained soils generate relatively low energy AE signals and these attenuate significantly over short distances. In order to monitor AE generated by deforming slopes formed of fine grained soils Dixon et al. (2003) conceived the active waveguide. The active waveguide is installed in a borehole that penetrates stable stratum below any shear surface or potential shear surface that may form beneath a slope. It comprises a metal waveguide rod or tube that provides a low resistance path for AE to travel from the source at the shear surface to the sensor at the ground surface. The annulus surrounding the waveguide is backfilled with granular soil. When the host slope deforms, the column of granular soil also deforms and this induces inter-particle friction and releases relatively high levels of AE that can propagate along the waveguide. Field trials and laboratory experiments (e.g. Dixon et al. 2003, Dixon et al. 2007 and Dixon et al. 2014a) have demonstrated that AE rates generated by active waveguides are proportional to the velocity of slope movement, and can therefore be used to monitor the stability of slopes and detect changes in rates of movement (i.e. accelerations and decelerations) in response to destabilising (i.e. rainfall) and stabilising (i.e. remediation) effects.

2.2. Retrofitting inclinometer casings

As discussed in Section 1, the traditional manually read inclinometer is the most commonly used instrument for subsurface deformation monitoring. However, it is an interval monitoring instrument and offers relatively low temporal resolution as measurements can only be taken when the casing is manually surveyed. Additionally, inclinometer casings become unusable when slope movements have induced magnitudes of curvature within the casing that will no longer allow the torpedo probe to pass the shear surface.

This paper proposes retrofitting inclinometer casings with acoustic real-time monitoring systems. A schematic of a retrofitted inclinometer can be seen in Figure 1. The benefits of retrofitting inclinometer casings with such a system include: the provision of continuous real-time information on slope movements; and continued operation beyond displacements that would normally be sufficient to render inclinometer casings unusable (i.e. not allow the probe to pass the shear surface). Any warnings of movement provided by the AE system could trigger the sending of an engineer to inspect the slope and manually read any adjacent inclinometer casings or instruments, or used to manage traffic if the warning level is severe enough.

2.3. Slope ALARMS system operation

An operation schematic of the AE monitoring system can be seen in Figure 2. When the host slope deforms the inclinometer casing also deforms along with the column of granular soil contained inside. This generates AE that can propagate along the waveguide to the ground surface where it is detected by a transducer and converted to an electrical signal. The electrical signal is then processed by the Slope ALARMS sensor which logs the number of post-threshold crossings (ring-down counts or RDC) per unit time. If the number of RDC detected within a pre-set time period exceeds a pre-determined threshold trigger level then a warning is initiated. The warning trigger levels are set based on an AE rate (RDC/hour)-Velocity calibration relationship where the RDC generated per unit time is proportional to the rate of slope movement (see Dixon et al. 2014a for further details). The warning trigger levels are set using the order of magnitude landslide velocity scale after Schuster & Krizek (1978) and Cruden & Varnes (1996), for example; slow (e.g. 1 mm/hour), moderate (e.g. 100 mm/hour), and rapid (e.g. 10,000 mm/hour). When the Slope ALARMS sensor detects an alarm state a warning is initiated. The sensor node communicates this warning via a WSN link to the communication node, and subsequently the communication node sends an SMS message to nominated persons/systems via GSM. Dependent on the severity of the warning a variety of actions could then be taken (e.g. send an engineer to inspect the slope or manage traffic).

3. Hollin Hill field trial

3.1. Introduction

Hollin Hill is a complex of interacting landslides situated 11 km to the west of Malton, North Yorkshire, UK [SE 68122 68852 (UK system), Latitude: 54.111044, Longitude: -0.95948786]. The landslides at Hollin Hill can be characterised as shallow rotational failures at the top of the slope that feed into larger-scale slowly moving lobes of slumped material further down the slope; the rotational features and active lobes extend approximately 150 m down the slope from the top of the hill (Figure 3). Movement typically occurs in the winter months when the slope is at its wettest. A detailed description of the site is provided by Chambers et al. (2011), Merritt et al. (2013) and Gunn et al. (2013) who have reported on the use of geophysical, remote sensing and geotechnical methods for the development of a 3D ground model of the Hollin Hill landslide complex.

3.2. Instrumentation installation

In December 2009 an active waveguide (AEWG2) and adjacent inclinometer casing (In2) were installed through one of the lobes at Hollin Hill (Cluster 2 in Figure 3). The active waveguide was installed in a 130 mm diameter borehole to a depth of 5.7 m below ground level. The waveguide comprised two 3 m lengths of 50 mm diameter 3 mm thick steel tubing connected with screw threaded couplings. The annulus around the steel tubing, which is located in the centre of the borehole, was backfilled with angular 5 to 10 mm gravel compacted in nominally 0.25 m high lifts. The top 0.3 m of the borehole was backfilled with a bentonite grout plug to seal against the ingress of surface water. The steel tube extended 0.3 m above ground level. The 70 mm diameter inclinometer casing was installed at this time approximately 1 m east of the waveguide with keyways orientated along the slope dip and strike directions. The inclinometer casing penetrates to a depth of 5.5 m below ground level and the annulus around the casing is grouted using medium stiffness cement bentonite grout.

The inclinometer casing was retrofitted with an active waveguide (AEWG In2) as shown in Figure 4b in December 2011. Previous surveys of the inclinometer casing revealed the lobe's shear surface to be at approximately 1.5 m below ground level. The bottom 2.8 m of the 5.5 m deep inclinometer casing was filled with Leighton Buzzard (LB) sand; it was not necessary for the waveguide to penetrate this depth as the active zone of AE generation would occur at the shear surface. As the diameter of the inclinometer casing was significantly smaller than the diameter of the borehole used for the traditional active waveguide; waveguide tubing with a smaller diameter and backfill with smaller particle size were required in order to install an active waveguide inside the inclinometer casing. A continuous 3 m long 25 mm diameter and 2 mm thick steel tube was installed vertically into the casing, bearing on top of the already placed LB sand. The annulus around the waveguide was subsequently backfilled with subangular LB sand (particle size between 0.6 mm and 2 mm) compacted in nominally 0.25 m high lifts. This column of LB sand was expected to generate AE in response to slope movements. The steel tube protruded 0.3 m above ground level.

Both active waveguides (i.e. traditional-AEWG2 and retrofitted inclinometer-AEWG In2) each have a transducer coupled to the waveguide at the ground surface. The transducers are connected to Slope ALARMS sensors via cables and are located inside protective covers (Figure 4a). The sensors are powered by batteries which are recharged by solar panels. Cumulative RDC are recorded and time stamped every 30 minutes, and monitoring is continuous.

A ShapeAccelArray (SAA) was installed 1 m west of the traditional active waveguide to a depth of 2.5 m in May 2013 to provide continuous subsurface deformation measurements for comparison with AE measurements in order to validate performance of the AE system Figure 4a).

3.3. AE response to slope movements

3.3.1. Traditional active waveguide and inclinometer comparison

A reactivated slope movement event that occurred at Hollin Hill in February 2010 is shown in Figure 5 (after Dixon et al. 2014a). The plot in Figure 5 shows two manual inclinometer readings with roughly 3 mm of shear surface displacement occurring between them. The triggering rainfall event can be seen prior to the sudden increase in AE rates, which is interpreted to indicate the onset of movement. The AE rate (RDC/hour) rapidly increases towards a peak value and then decreases, resulting in a bell shaped log-normal curve. This signature shape of the AE rate-time curve is characteristic of reactivated slope movement events that have occurred at Hollin Hill and at other sites. Such reactivated slope kinematics are explained by an initial acceleration of the slide mass due to increasing pore-water pressures on the shear plane, and hence reducing shear strength and stability, and a peak velocity is approached. This is followed by a deceleration of movements as pore-water pressures dissipate and due to mobilisation of shear resistance internally in the slide mass and through remoulding at the landslide toe. Leroueil (2001) presented a conceptual velocity-time profile for reactivated slope movements that possessed the shape of a normal distribution. The event shown in Figure 5 is analogous to such behaviour; hence, AE rates generated by the system are directly proportional to the velocity of slope movement. This generates the ‘S’-shaped displacement-time curve which was derived from the AE rate data (through determination of the rate of change with respect to time and equating the area under the bell-shaped curve to the magnitude of displacement measured by the adjacent inclinometer) and provides increased temporal resolution for the deformation event (as in Dixon et al. 2014a).

3.3.2. Retrofitted inclinometer active waveguide and SAA comparison

Figure 6a shows the horizontal displacement (recorded by the SAA), AE rate (RDC/hour) measured using AEWG In2 and rainfall time series for a series of reactivated slope movements that occurred in January-February 2014. Figure 6b shows the cumulative RDC trend superimposed on the same time series. The periods of small magnitude low velocity slope movements shown in Figure 6 were preceded by periods of rainfall which induced transient elevations in pore-water pressure and reductions in stability. The slope movements strained the inclinometer casing along with the active waveguide contained inside and this generated AE. This resulted in a cumulative RDC-time series proportional to the displacement-time series (i.e. confirming that the AE rates generated are proportional to the rate of slope movement). The AE rates generated by the retrofitted inclinometer (Figure 6a) were lower magnitude than those generated by the traditional active waveguide (Figure 5) and this was expected due to the smaller particle size of the backfill (i.e. sand instead of gravel) which generates AE signals with smaller amplitude. The field trial at Hollin Hill demonstrates that inclinometer retrofitted active waveguides can detect and provide continuous information on slope movements with high temporal resolution. Figure 7 shows selected surveys from the SAA for the same period as in Figure 6 which confirms the depth of the shear surface to be at approximately 1.5 m below ground level. It is important to note that the time series of measurements presented from the retrofitted inclinometer active waveguide (i.e. January-February 2014 in Figures 6a,b) occurred 14 months after other inclinometer casings at the same site (one on the same lobe) became unusable as the probes could no longer pass the shear surface due to excessive curvature (all the inclinometer casings were installed at the same time in December 2009/January 2010 and therefore will have experienced similar magnitudes of total displacement, as described in Dixon et al. 2014a). This is of significance as it demonstrates the ability to not only convert inclinometer casings to continuous real-time monitoring systems, but also to significantly extend their lifespan, using the AE technique.

4. Summary

The concept of retrofitting inclinometer casings with acoustic real-time monitoring systems has been introduced. The operation of the Slope ALARMS system has been described and a field trial of its operation at Hollin Hill, North Yorkshire, UK has been presented. The results demonstrate that AE rates generated by active waveguides in response to slope movements are directly proportional to the rate of slope movement. The study also shows that inclinometer casings retrofitted with active waveguides can provide continuous information on slope movements. This conversion can also extend the useful lifespan of inclinometer casings. By employing existing inclinometer casings that have been installed at relatively high costs, the Slope ALARMS monitoring approach can provide cost effective real-time information that could be used in the protection of people and infrastructure by operators and practitioners. Active waveguides and the Slope ALARMS monitoring system are being trialled at various natural and man-mode slopes throughout the UK (e.g. Dixon et al. 2014a,b) Italy (Dixon et al. 2012b), Austria and Canada (Smith et al. 2014) in order to assess performance in the field environment and compare against other monitoring instruments and techniques.

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References

Chambers, J.E, P.B Wilkinson, O Kuras, J.R Ford, D.A Gunn, P.I Meldrum, C.V.L Pennington, A.L Weller, P.R.N Hobbs, and R.D Ogilvy. 2011. Three-dimensional Geophysical Anatomy of an Active Landslide in Lias Group Mudrocks, Cleveland Basin, UK. *Geomorphology* 125 (4): 472–484.

Dijkstra, T A, and N Dixon. 2010. Climate Change and Slope Stability in the UK: Challenges and Approaches. *Quarterly Journal of Engineering Geology and Hydrogeology* 43: 371–385.

Dixon, N. Hill, R. & Kavanagh, J. 2003. Acoustic emission monitoring of slope instability: Development of an active wave guide system. *Institution of Civil Engineers Geotechnical Engineering Journal*, 156, 2, 83-95.

Dixon, N. & Spriggs, M. 2007. Quantification of slope displacement rates using acoustic emission monitoring. *Canadian Geotechnical Journal*, 44, 6, 966-976.

Dixon, N. & Spriggs, M. 2011. Apparatus and method for monitoring soil slope displacement rate. *UK Patent Application GB 2467419A,* Awarded May 2011.

Dixon, N, M P Spriggs, P Meldrum, and E Haslam. 2012a. Field Trial of an Acoustic Emission Early Warning System for Slope Instability. In *Landslides and Engineered Slopes: Protecting Society Through Improved Understanding*, 1399–1404.

Dixon, N, M P Spriggs, G Marcato, and A Pasuto. 2012b. Landslide Hazard Evaluation by Means of Several Monitoring Techniques, Including an Acoustic Emission Sensor. In *Landslides and Engineered Slopes: Protecting Society through Improved Understanding*, 1405–1411.

Dixon, N, M P Spriggs, A Smith, P Meldrum, and E Haslam. 2014a. Quantification of Reactivated Landslide Behaviour using Acoustic Emission Monitoring. Landslides, 1-12. DOI: 10.1007/s10346-014-0491-z

Dixon, N, R Moore, M P Spriggs, A Smith, P Meldrum, and R Siddle. 2014b. Performance of an Acoustic Emission Monitoring System to Detect Subsurface Ground Movement at Flat Cliffs, North Yorkshire, UK. In IAEG XII Congress - Torino.

Gibson, A D, M G Culshaw, C Dashwood, and C V L Pennington. 2013. Landslide Management in the UK - the Problem of Managing Hazards in a ‘Low-Risk’ Environment. *Landslides*, *10*(5), 599-610.

Gunn, D A, J E Chambers, P R N Hobbs, J R Ford, P B Wilkinson, G O Jenkins, and A Merrit. 2013. Rapid Observations to Guide the Design of Systems for Long-Term Monitoring of a Complex Landslide in the Upper Lias Clays of North Yorkshire, UK. *Quarterly Journal of Engineering Geology and Hydrogeology* 46 (3): 323–336.

Hutchinson, J N. 1988. General Report: Morphological and Geotechnical Parameters of Landslides in Relation to Geology and Hydrogeology. In *Proc 5th International Symposium on Landslides, Lausanne*, 3–35.

Koerner, R.M. McCabe, W.M. & Lord, A.E. 1981. Acoustic emission behaviour and monitoring of soils. In *Acoustic Emission in Geotechnical Practice*, ASTM STP 750, pp. 93-141.

Leroueil, S. 2001. Natural Slopes and Cuts: Movement and Failure Mechanisms. *Geotechnique* 51 (3): 197–243.

Merritt, A.J, J.E Chambers, W Murphy, P.B Wilkinson, L.J West, D.A Gunn, P.I Meldrum, N Kirkham and N. Dixon. 2013. 3D Ground Model Development for an Active Landslide in Lias Mudrocks Using Geophysical, Remote Sensing and Geotechnical Methods. *Landslides*, pp 14. DOI 10.1007/s10346-013-0409-1

Petley, D N. 2012. Global Patterns of Loss of Life from Landslides. *Geology, Geological Society of America* 40 (10): 927–930.

Schuster, R.L. & Krizek, R.J. (eds.) 1978. *Landslides Analysis and Control, Transportation Research Board Special Report 176*, National Academy of Science, Washington.

Smith, A, N Dixon, N Berg, A Take, and D Proudfoot. 2014. Listening for Landslides: Method, Measurements and the Peace River Case Study. *In Geohazards 6*.

Take, A, and M D Bolton. 2011. Seasonal Ratcheting and Softening in Clay Slopes, Leading to First-Time Failure. *Geotechnique* 61 (9): 757–769.

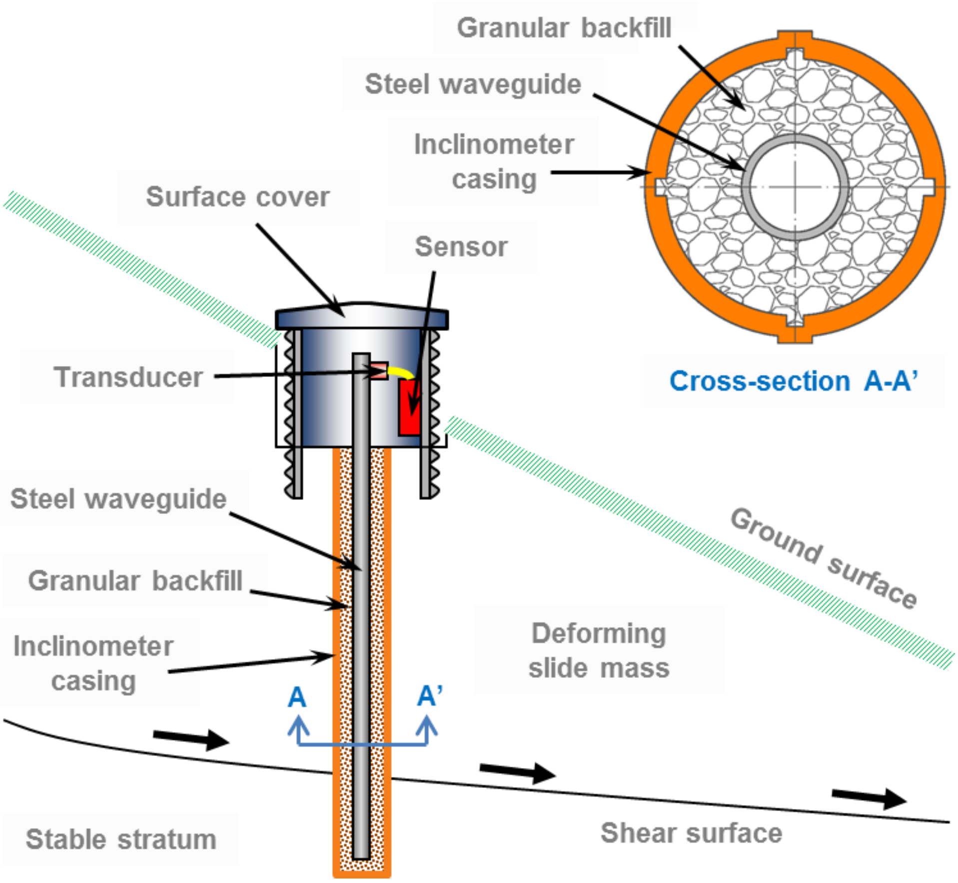

Figure 1. Schematic of an active waveguide retrofitted inside an inclinometer casing through a deforming soil slope with a transducer and Slope ALARMS sensor coupled at the ground surface and protected by a cover (after Dixon et al. 2012a)

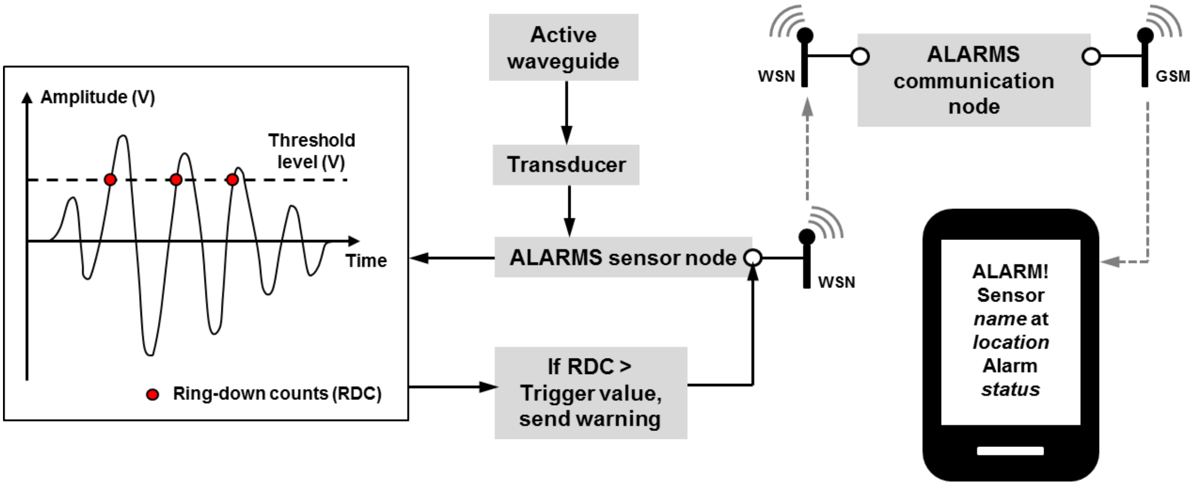

Figure 2. Schematic of operation of the Slope ALARMS system including sensor node and communication system

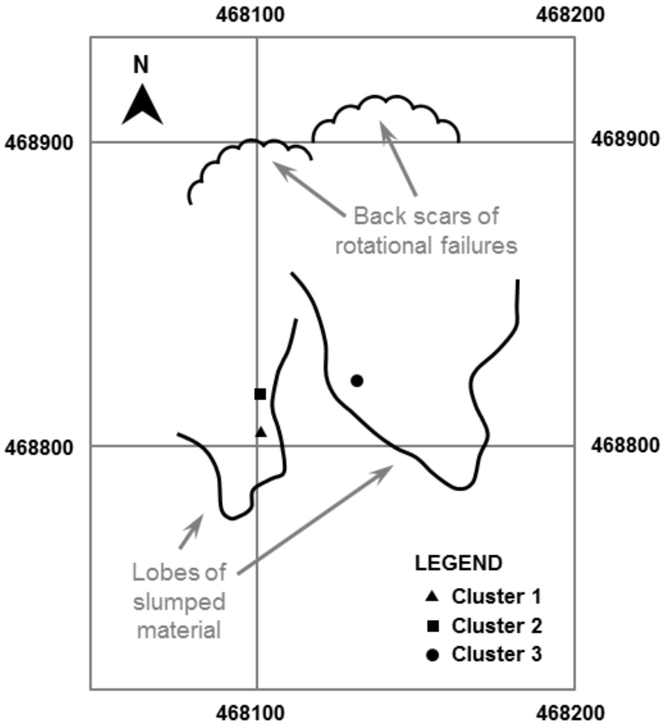

Figure 3. Site plan of Hollin Hill landslide with instrumentation clusters highlighted (UK Ordnance Survey grid reference system)

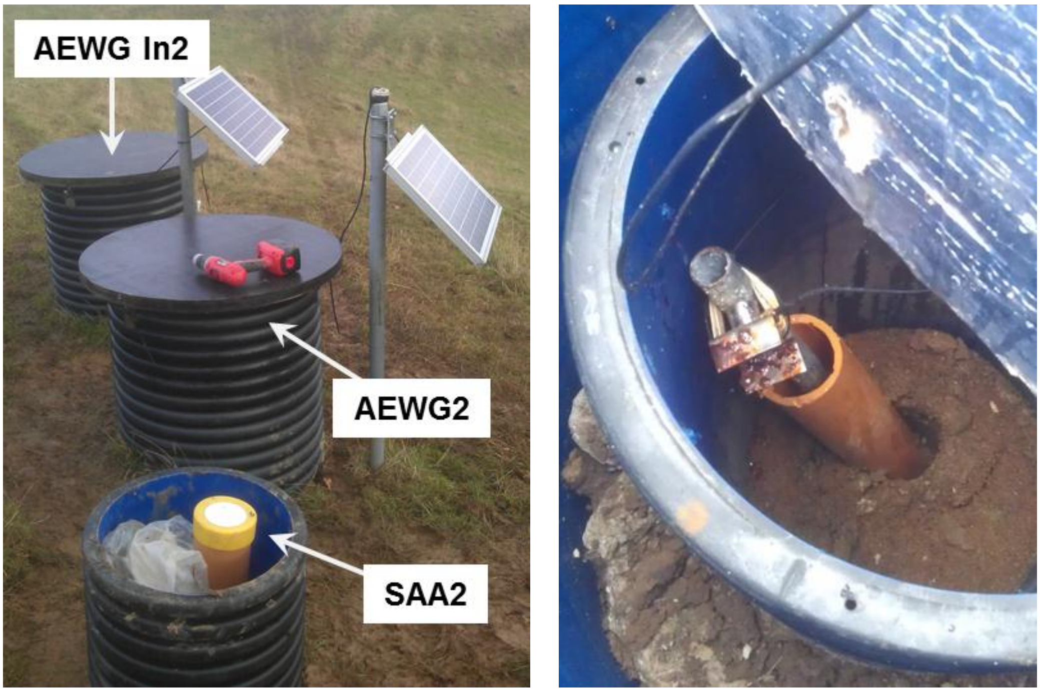

Figure 4. Photographs of instrumentation installation at Cluster 2 at Hollin Hill; a) surface covers, and b) deformed retrofitted inclinometer (AEWG In2)

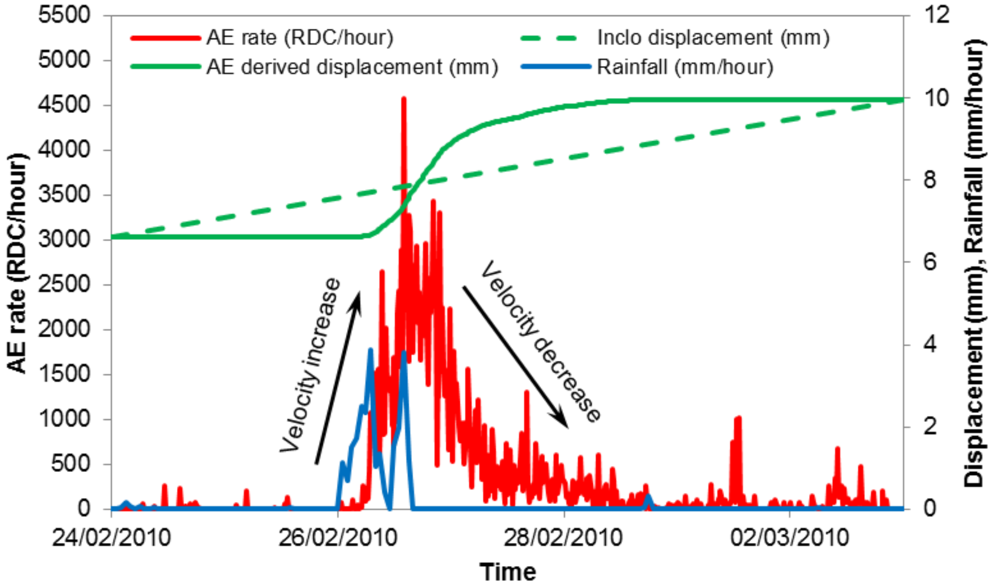

Figure 5. Typical active waveguide AE response to a reactivated slope movement event at Hollin Hill (after Dixon et al. 2014a)

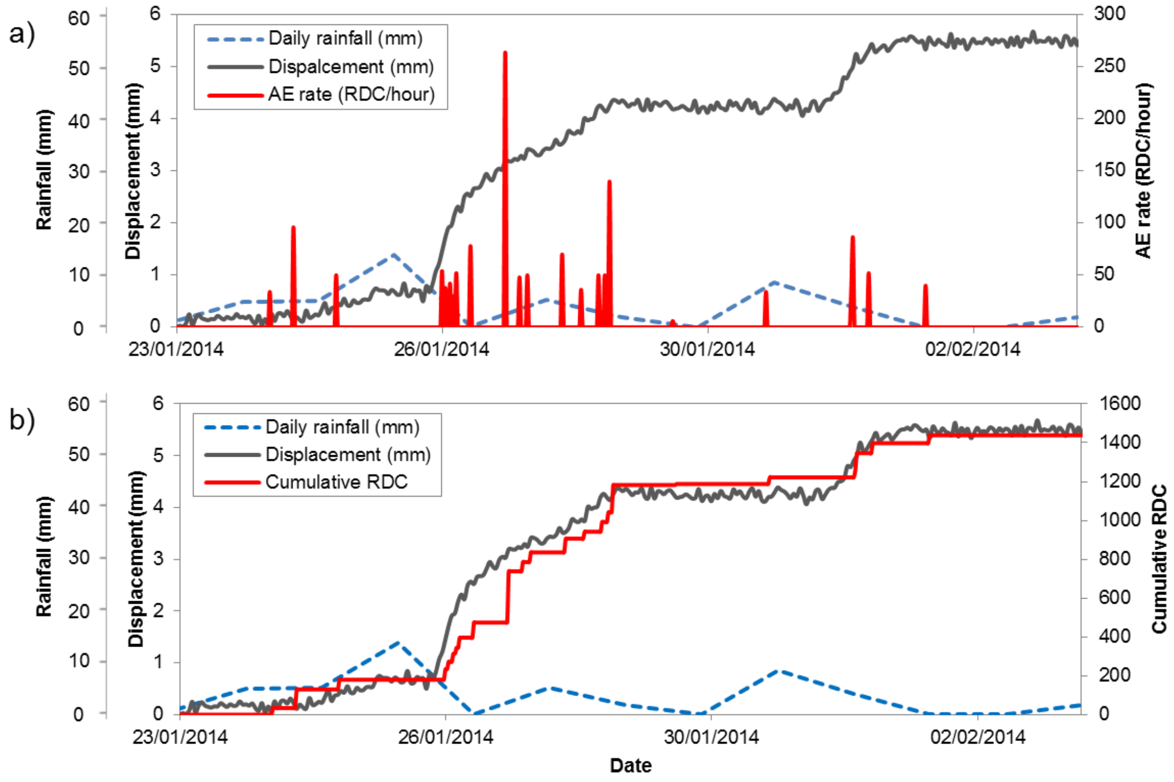

Figure 6. Displacement-, AE- and rainfall-time series for a period of reactivated slope movements at Hollin Hill

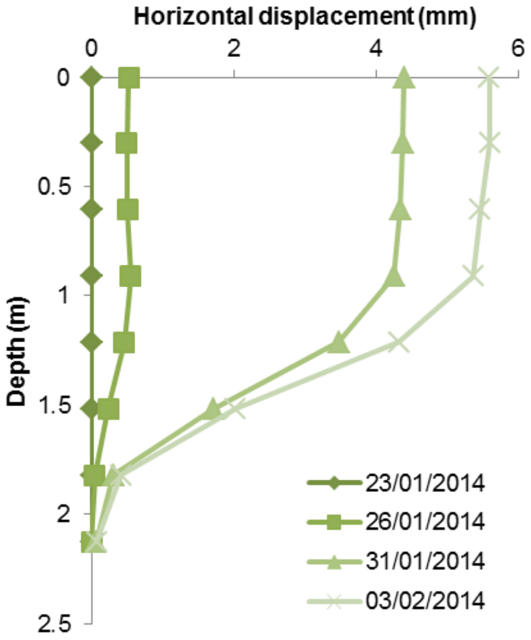

Figure 7. Deformation vs. depth profile recorded by the SAA for the period of slope movements presented in Figure 6